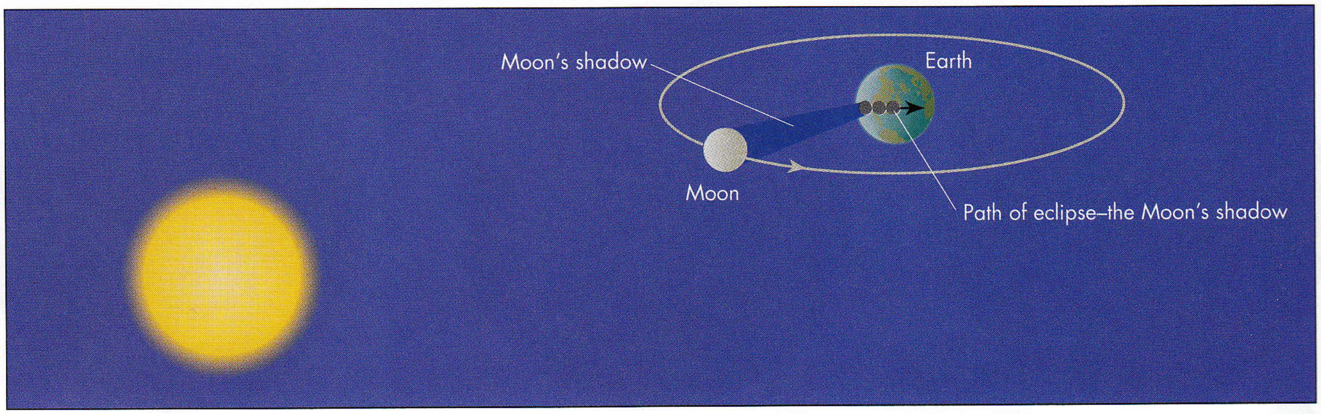

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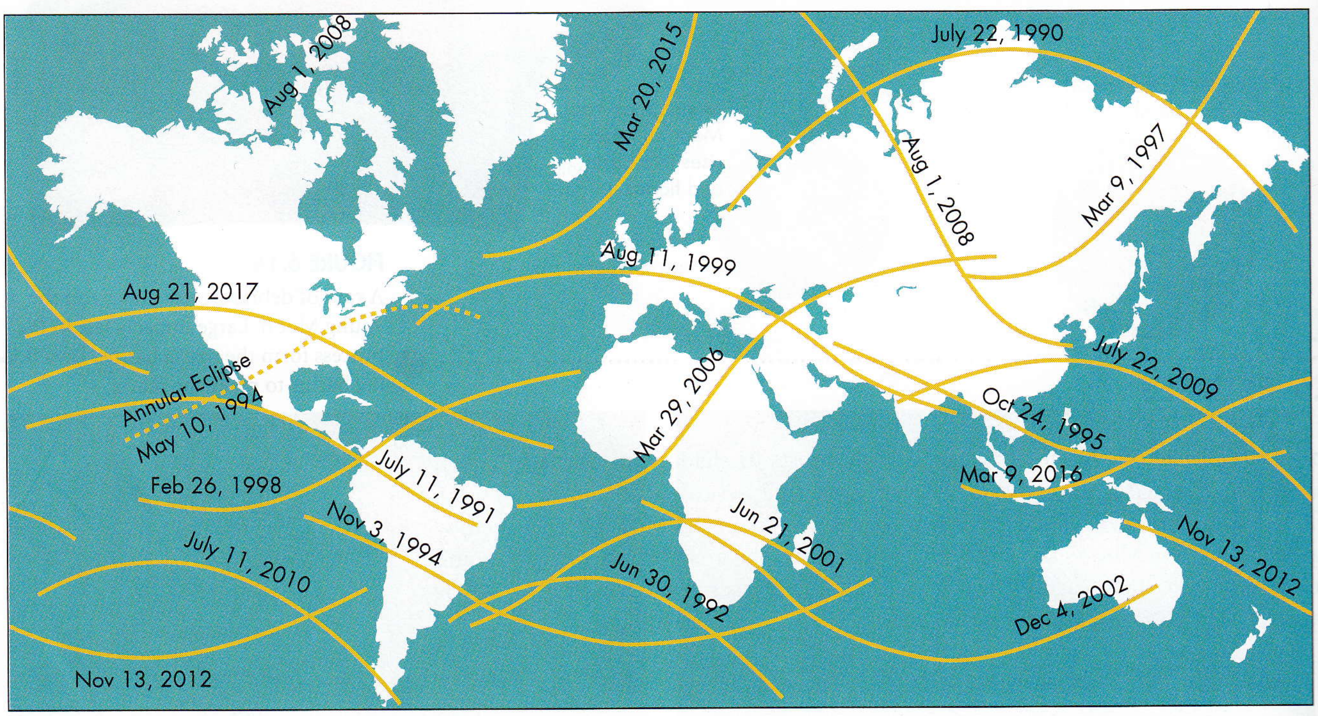


B

FIGURE 6.15

(A) Sketch of how the Moon's shadow travels across the Earth. (B) Location of some recent and upcoming total solar eclipses.

(From Kuhn, Karl F. *Astronomy*, p. 204, St. Paul, Minn.: West Publishing, 1989.)

Rarity of Eclipses

Eclipses and the Moon's orbital inclination

Eclipses are rare because the Moon's orbit around the Earth is tilted with respect to the Earth's orbit around the Sun (see fig. 6.12). Without that tilt, we would have lunar and solar eclipses every month, but with the tilt, the Moon lies above the Earth's orbit for half the month and below it for the other half. The result is that at full moon, the Earth's shadow generally falls either above or below the Moon, and at new moon, the Moon's shadow falls below or above the Earth, as shown in figure 6.16. Thus, eclipses do not generally occur very often. How, then, are eclipses possible?

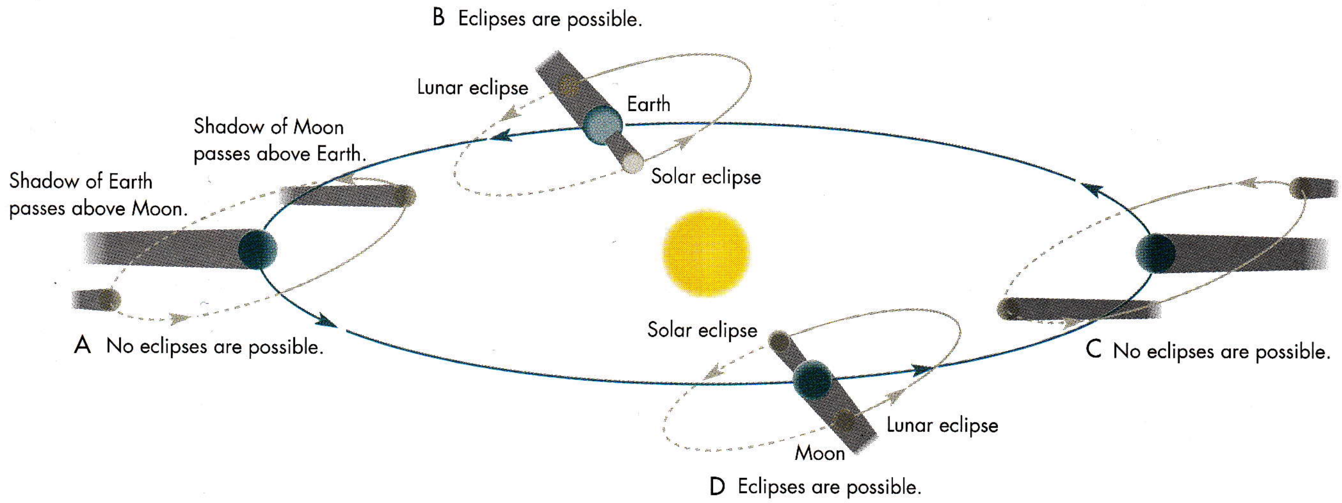


FIGURE 6.16

The Moon's orbit keeps approximately the same orientation as the Earth orbits the Sun. Because of its orbital tilt, the Moon generally is either above or below the Earth's orbit. Thus, the Moon's shadow rarely hits the Earth, and the Earth's shadow rarely hits the Moon, as you can see in (A) and (C). Eclipse seasons occur when the Moon's orbital plane, if extended, intersects the Sun. A solar eclipse will then occur at new moon and a lunar eclipse at full moon, as you can see in (B) and (D).

TABLE 6.2
Pairing of Eclipses at Eclipse Seasons

MAY 16, 2003 LUNAR (TOTAL) Americas, Europe, Africa	**MAY 31, 2003 SOLAR (ANNULAR*)** Northwestern America, Greenland, Europe
NOV 9, 2003 LUNAR (TOTAL) Americas, Europe, Africa, central Asia	**NOV 23, 2003 SOLAR (TOTAL)** Antarctica, extreme southern South America, Australia, New Zealand

*A solar eclipse is annular if it occurs when the Moon is near the point in its orbit farthest from Earth. Under that condition, the Moon will not quite cover the Sun, even though it is exactly in line with it. The edge of the Sun, therefore, remains uncovered all around the Moon and appears as a bright ring, or annulus.

As the Earth orbits the Sun, the Moon's orbit keeps nearly the same direction of tilt, as shown in figure 6.16. This orbital tilt is kept fixed—like that of the spinning Earth—by a gyroscopic effect or, more technically, by the conservation of angular momentum. The result is that twice each year, the Moon's orbital plane (if extended) passes through the Sun, as shown in figure 6.16. At those times—**eclipse seasons**—eclipses will happen when the Moon crosses the Earth's orbital plane (the ecliptic*). Table 6.2 shows that in 2003, the eclipse seasons are in May and November. Only in those months can eclipses happen: at other times, the shadows of the Earth and Moon always fall on empty space.

You can also see from figure 6.16 that when a solar eclipse occurs at new moon, conditions are right for a lunar eclipse to happen at either the previous or the following full moon. Thus, eclipses generally occur in pairs, with a solar eclipse followed approximately 14 days later by a lunar eclipse, or vice versa, as shown for the 2003 eclipses listed in table 6.2.

*As mentioned in chapter 1, this is the reason the ecliptic is so named.

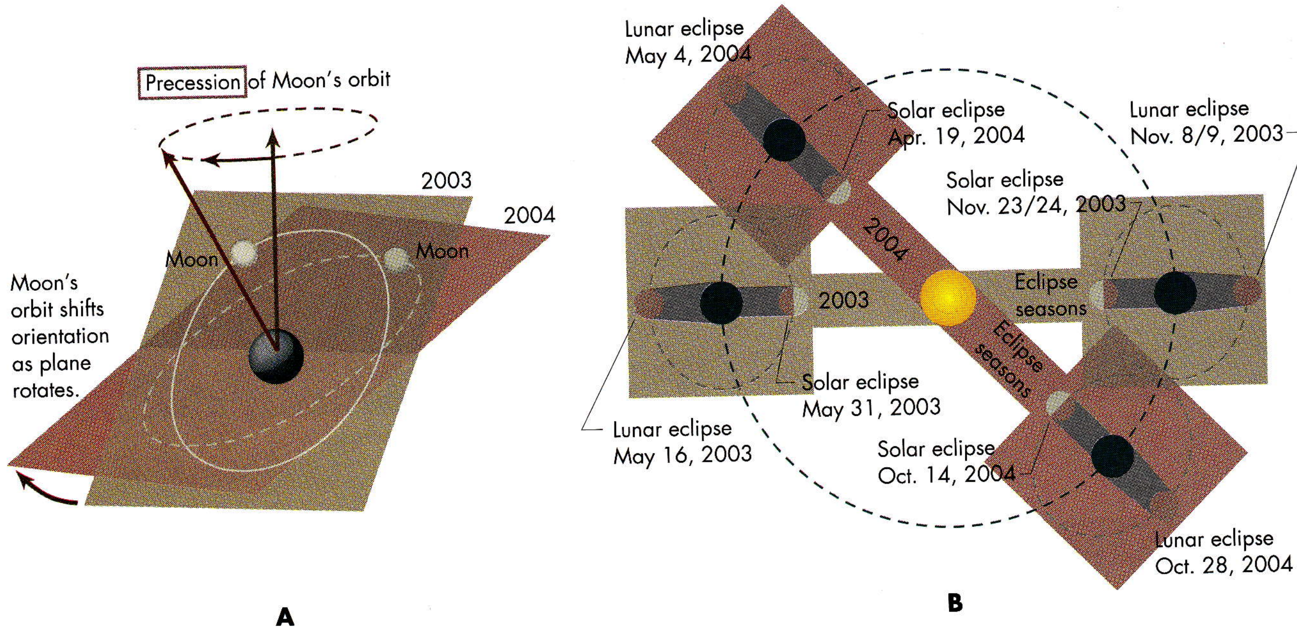


FIGURE 6.17
(A) Precession of the Moon's orbit. Notice its similarity to twisting a tilted book that has one edge resting on a table. (B) Precession of the Moon's orbit causes eclipses to come at different dates in successive years.

This simple pattern does not always work, because the tilt of the Moon's orbit is not exactly fixed. An imaginary line perpendicular to the orbit (shown in fig. 6.17A) slowly changes direction just as the Earth's rotation axis does. That is, the Moon's orbit precesses, swinging once around about every 18.6 years. This orbital precession makes the dates of the eclipse seasons shift by 1/18.6 year (about 20 days) each year. Thus, in 2004, eclipses occur about 2 weeks earlier than in 2003, as shown in figure 6.17B.

If one of the eclipse seasons occurs in early January with the next in June, a third season may sometimes happen in late December. As a result, as many as five solar and two lunar eclipses or four solar and three lunar eclipses can occur each year. No matter when the eclipse season falls, at least two solar eclipses must happen each year, but that does not mean they will be visible to an observer at a given location, since the eclipse may be visible only from another part of the Earth. Because the Moon is so small compared with the Earth, its shadow is small, and therefore, you can see a solar eclipse only from within a narrow band, as illustrated in figure 6.15. Lunar eclipses, however, are visible from anywhere the Moon is above the horizon at the time of the eclipse.

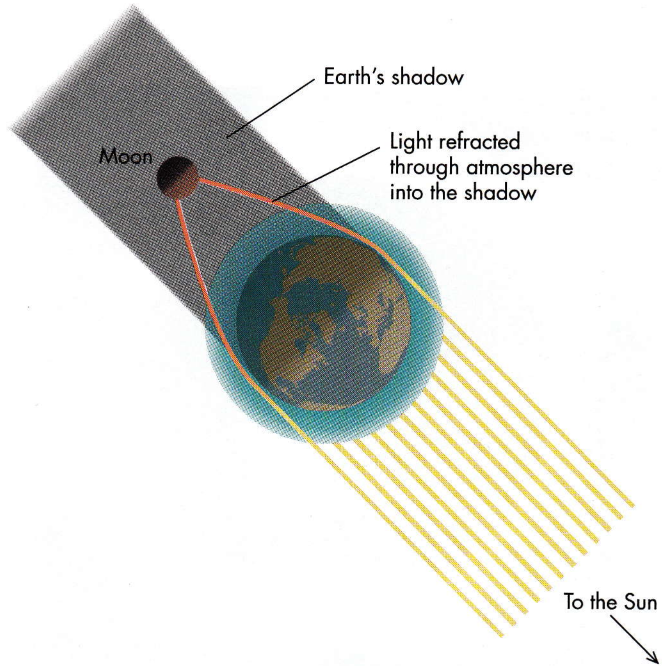
Appearance of Eclipses

Eclipses are beautiful and marvelous events and well worth watching. During a lunar eclipse, the Earth's shadow gradually spreads across the Moon's face, cutting an ever deeper dark semicircle out of it. The shadow takes about an hour to completely cover the Moon and produce totality. At totality, the Moon generally appears a deep ruddy color, almost as if dipped in blood. Sometimes it even disappears. After totality, the Moon again becomes lit, bit by bit, reverting to its unsullied, silvery light.

A little light falls on the Moon even at totality because the Earth's atmosphere bends some sunlight into the shadow, as shown in figure 6.18. The light reaching the Moon is red because interactions with air molecules remove the blue light as it passes through our atmosphere and is bent, exactly as happens when we see the setting Sun.

Be extremely careful when watching a solar eclipse. Looking at the Sun through improper filters will blind you. A safer way is to *not* look directly at the Sun but to use eyepiece projection to view the Sun. Hold a piece of paper about a foot from the eyepiece of a small telescope (or even binoculars), and a large image of the Sun will be visible on it. This method also allows many people to watch the eclipse simultaneously.

A



B

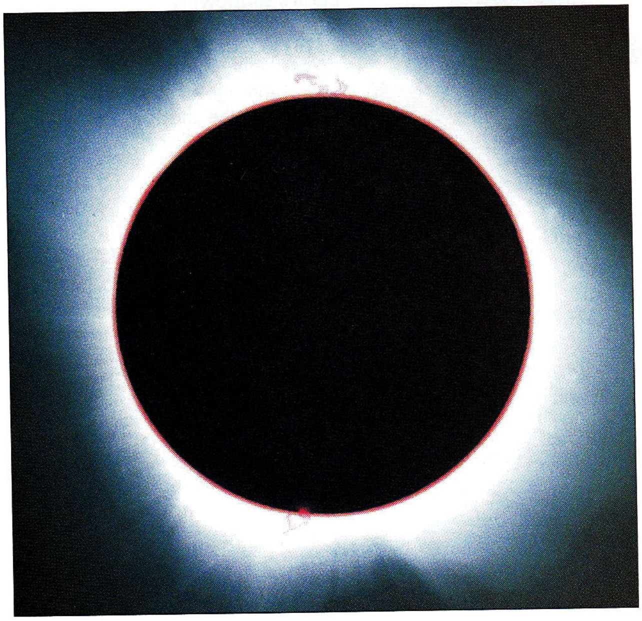
FIGURE 6.18

(A) Photograph of a total lunar eclipse.
(Photo by Dennis di Cicco/Sky and Telescope.)
(B) As sunlight falls on the Earth, some passes through the Earth's atmosphere and is slightly bent so that it ends up in the Earth's shadow. In its passages through our atmosphere, most of the blue light is removed, leaving only the red. That red light then falls on the Moon, giving it its ruddy color at totality.

A solar eclipse begins with a black "bite" taken out of the Sun's edge as the Moon cuts across its disk. Such partial eclipses are fun to watch but should be observed with care so as not to hurt your eyes. However, unless a large part of the Sun is covered by the Moon, you may not even notice an eclipse is happening. On the other hand, if you are fortunate enough to be at a location where the eclipse is total, you will see one of the most amazing sights in nature.

As the moment of totality approaches, the landscape takes on an eerie light. Shadows become incredibly sharp and black: even individual hairs on your head cast crisp shadows. Sunlight filtering through leaves creates tiny bright crescents on the ground. Seconds before totality, pale ripples of light sweep across the ground and to the west the deep purple shadow of the Moon hurtles down on you at more than 1000 miles an hour. In one heartbeat you are plunged into darkness. Overhead, the sky is black, and stars may appear. The corona of the Sun—its outer atmosphere—gleams with a steely light around the Moon's black disk. Perhaps a solar prominence—a tiny, glowing, red flamelike cloud in the Sun's atmosphere—may protrude beyond the Moon's black disk (fig. 6.19). Birds call as if it were evening. A deep chill descends because for a few minutes the Sun's warmth is blocked by the Moon. The horizon takes on sunset colors: the deep blue of twilight with perhaps a distant cloud in our atmosphere glowing orange. As the Moon continues in its orbit, it uncovers the Sun, and instantly, it is daylight again. Now the cycle continues in reverse. If you ever have the chance to see a total eclipse, do it. It is worth traveling hundreds of miles to see.

The rarity of eclipses may lead you to think that the astronomical effects of the Moon are uncommon. A day spent by the ocean, however, will reveal a far more common and more powerful lunar influence.



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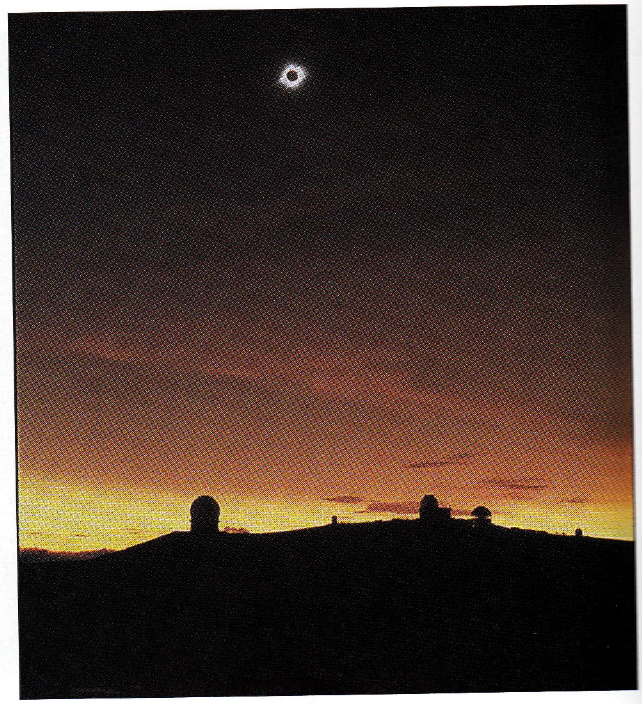

B

FIGURE 6.19

(A) Photograph of a total solar eclipse. The bright halo of light is the Sun's corona, its outer atmosphere.

(Photo by Dennis di Cicco/Sky and Telescope.)

(B) The landscape is eerily lit during a total solar eclipse. The dark color of the sky is the Moon's shadow.

(Courtesy of Richard Wainscoat.)

6.6 TIDES

Anyone who has spent even a few hours by the sea knows that the ocean's level rises and falls during the day. A blanket set on the sand 10 feet from the water's edge may be inundated an hour later, or a boat pulled ashore may be left high and dry. This regular change in the height of the ocean is called the **tides** and is caused mainly by the Moon.

Tidal forces

Cause of Tides

Just as the Earth exerts a gravitational pull on the Moon, so too the Moon exerts a gravitational attraction on the Earth and its oceans and draws material toward it. The attraction is stronger on the side of the Earth near the Moon and weaker on the far side (see fig. 6.20) because the force of gravity weakens with distance (recall Newton's law of gravity, p. 85). The difference between the strong force on one side and the weaker force on the other is called a **differential gravitational force.**

The differential gravity draws water in the oceans into a **tidal bulge** on the side of the Earth facing the Moon, as shown in figure 6.20.* But curiously, it creates an identical tidal bulge on the Earth's far side. This second tidal bulge can be viewed as a result

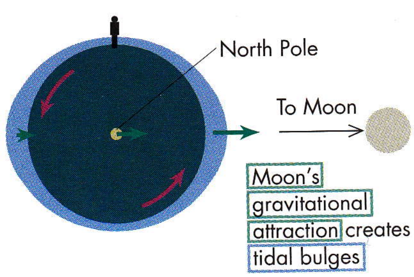

FIGURE 6.20
Tides are caused by the Moon's gravity creating tidal bulges.

*The tidal bulges do not exactly align with the Moon for reasons we will discuss in the section below on tidal braking.

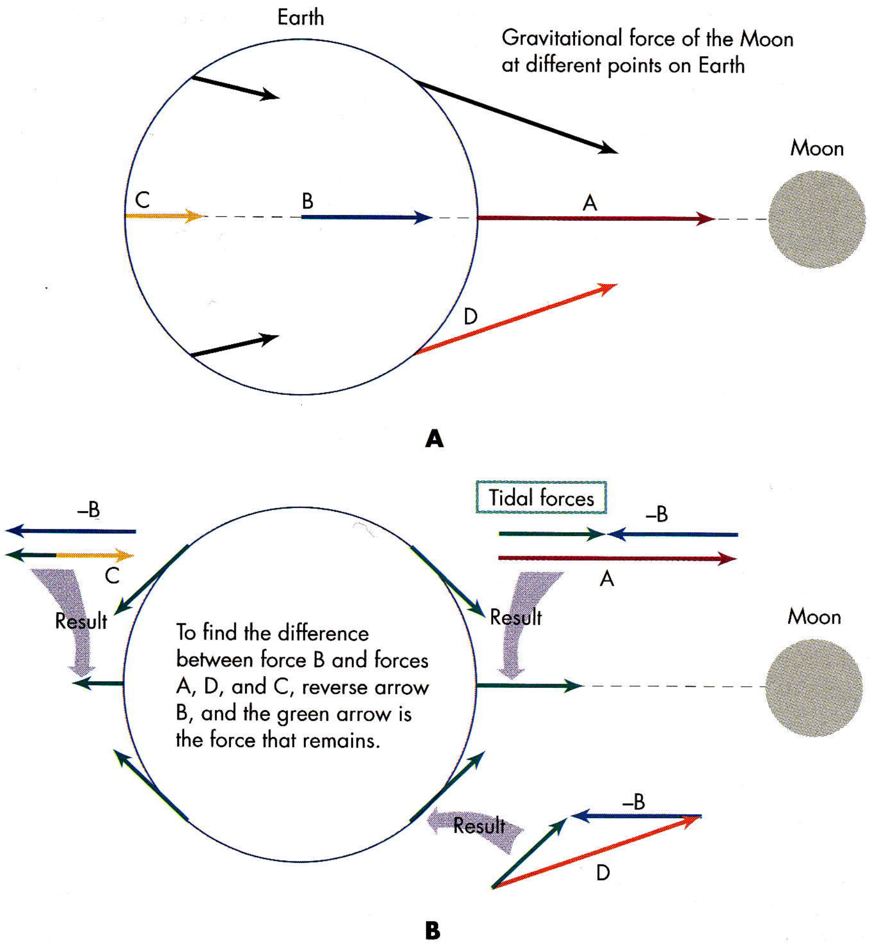

FIGURE 6.21
(A) Arrows schematically show Moon's gravitation force at different points on the Earth. (B) Tidal forces from the point of view of an observer on the Earth. These arrows represent the difference between the Moon's gravitational force at a given point and its force at the Earth's center.

of the Moon's gravity pulling the Earth "out from under" the water on the far side. A better way to view it, however, is to examine the Moon's gravitational forces on the Earth and its oceans as seen by a person on the Earth, as shown in figure 6.21.

The arrows in figure 6.21A represent the Moon's gravitational force on the Earth. Points on the side of the Earth near the Moon (A) undergo a stronger pull toward the Moon than those on the far side (C), and so arrow A is longer than C. Likewise, arrow A is longer than B, which represents the Moon's pull on the center of the Earth, and B is longer than C.

Because the force at A is larger than the force at B, matter at A will be pulled away from B. This creates one tidal bulge. But B in turn is pulled away from C and creates the second tidal bulge. If we now draw a second set of arrows to represent the *difference* between the force at B and at every other point (the differential gravitational force), we find the forces illustrated in figure 6.21B. These drive the oceans into the bulges* that we see.

An analogy may help you better understand tidal forces. Imagine holding a child by its hands and swinging it around you in a circle. As you swing the child, its feet fly out away from you because of their inertia, even though you are holding it by its hands. So too as the Earth and Moon swing around their common center of mass, the Moon's gravity pulls water on the side of the Earth toward the Moon into a bulge, while inertia makes water on the far side "fly out" into a second bulge.

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*Tides also occur in the atmosphere and solid ground, but the latter are very small because the ground is rigid and cannot move as easily as water or air.

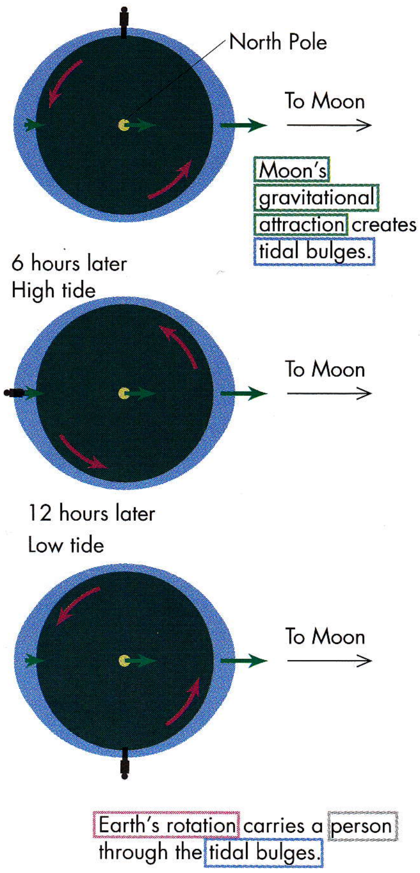


FIGURE 6.22
As the Earth rotates, it carries points along the coast through the tidal bulges. Because there are two bulges where the water is high and two regions where the water is low, we get two high tides and two low tides each day at most coastal locations.

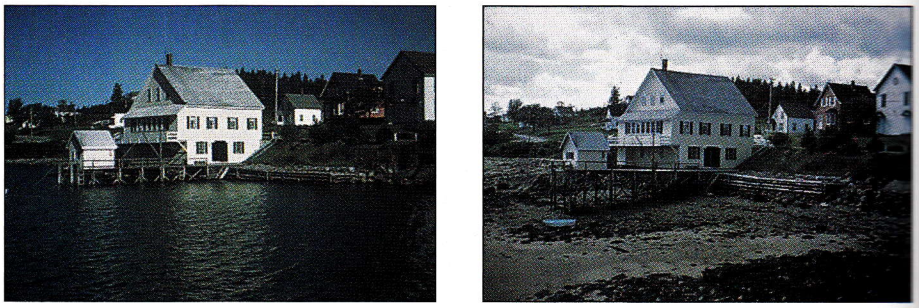
In the previous discussion, we have ignored the Earth's rotation. The tidal bulges are aligned approximately with the Moon, but the Earth spins. Its rotation therefore carries us first into one bulge and then the next. As we enter the bulge, the water level rises, and as we leave it, the level falls. Because there are two bulges, we are carried into high water twice a day, creating two high tides. Between the times of high water, as we move out of the bulge, the water level drops, making two low tides each day (fig. 6.22).

This simple picture must be altered to account for the inability of the ocean to flow over land areas. Thus, water tends to pile up at coastlines when the tidal bulge reaches shore. In most locations, the tidal bulge has a depth of about 2 meters (6 feet), but it may reach 10 meters (30 feet) or more in some long narrow bays (as you can see in the photographs of high and low tides along the Maine coast) and may even rush upriver as a tidal bore—a cresting wave that flows upstream. On some rivers, surfers ride the bore upstream on the rising tide.

The motion of the Moon in its orbit makes the tidal bulge shift slightly from day to day. Thus, high tides come about 50 minutes later each day, the same delay as in moonrise, discussed in chapter 1.

Solar Tides

The Sun also creates tides on the Earth, but although the Sun is much more massive than the Moon, it is also much farther away. The result is that Sun's tidal force on the Earth is only about one-half the Moon's. Nevertheless, it is easy to see the effect of their tidal cooperation in spring tides, which are abnormally large tides that occur at new and full moon. At those times, the lunar and solar tidal forces work together, adding their separate tidal bulges, as illustrated in figure 6.23A. Notice that spring tides have nothing to do with the seasons; rather, they refer to the "springing up" of the water at new and full moon.



High tide Low tide

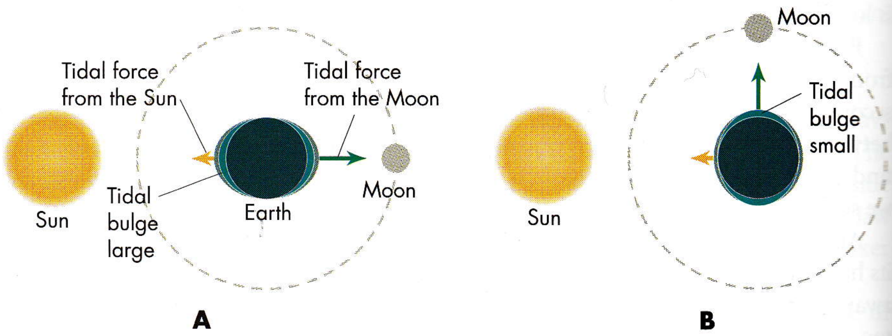


FIGURE 6.23
The Sun's gravity creates tides too, though its effect is only about one-half that of the Moon. (A) The Sun and Moon each create tidal bulges on the Earth. When the Sun and Moon are in line, their tidal forces add together to make larger-than-normal tides. (B) When the Sun and Moon are at 90° as seen from Earth, their tidal bulges are at right angles and partially nullify each other, creating smaller-than-normal tidal changes.

It may seem odd that spring tides occur at both new and full moon because the Moon and Sun pull together when the Moon is new but in opposite directions when it is full. However, both the Sun and Moon create two tidal bulges, and the bulges add regardless of whether the Sun and Moon are on the same or opposite sides of the Earth. On the other hand, at first and third quarters, the Sun and Moon's tidal forces work at cross-purposes, creating tidal bulges at right angles to one another, as shown in figure 6.23B. The so-called neap tides that result are therefore not as extreme as normal high and low tides.

Tidal Braking

Tides create forces on the Earth and Moon that slow their rotation, a phenomenon known as **tidal braking.** Figure 6.24 shows how the Moon tidally brakes the Earth. As the Earth spins, friction between the ocean and the solid Earth below drags the tidal bulge ahead of the imaginary line joining the Earth and Moon, as depicted in figure 6.24. The Moon's gravity pulls on the bulge, as shown by the arrow in the figure, and holds it back. The resulting drag is transmitted through the ocean to the Earth, slowing its rotation the way a brake shoe on a car or your hand placed on a spinning bicycle wheel slows the wheel.

As the Earth's rotation slows, the Moon accelerates in its orbit, moving farther from the Earth, as required by the need to conserve angular momentum. The Moon accelerates because the tidal bulge it raises on the Earth exerts a gravitational force back on the Moon (as predicted by Newton's third law of motion), which pulls the Moon ahead in its orbit, as shown by the arrows in figure 6.24. That acceleration makes the Moon move away from the Earth at about 3 centimeters (roughly 1 inch) per year, a tiny increase in the Earth-Moon distance, but nevertheless detectable with laser range finders. Thus, the Moon was once much closer to the Earth and the Earth spun much faster, perhaps as rapidly as once every 5 hours several billion years ago. Over that immense period of time, the Moon has receded to its present distance, and the Earth's rotation has slowed to 24 hours. These processes occur even now: tidal braking lengthens the day by about 0.002 seconds each century.

Tidal braking is also the reason the Moon always keeps the same face to the Earth. Just as the Moon raises tides, which slow the Earth, the Earth raises tides on the Moon, which slow it. These lunar tides distort the Moon's crust and have braked the Moon severely, locking it into synchronous rotation. The Moon's braking of the Earth will eventually make the Earth rotate synchronously with the Moon's orbital motion.

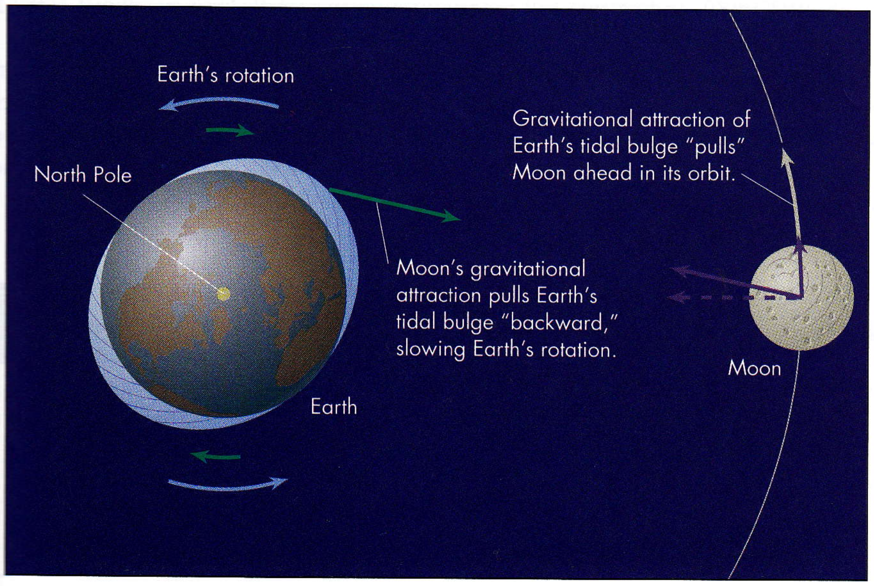


FIGURE 6.24
Tidal braking slows the Earth's rotation and speeds up the Moon's motion in its orbit.

Billions of years from now, the Earth and Moon will orbit so that each constantly presents the same face to the other: the Moon will then be visible only from one side of the Earth! Similar tidal effects have locked some of the moons of other planets into synchronous rotation, but the planets themselves have not been noticeably slowed. On the other hand, tidal braking by the Sun probably slowed the rotation of Mercury and Venus.

The Moon's gravitational pull on the Earth may also stabilize our climate. Astronomers have recently discovered with computer simulations that the tilt of a planet's rotation axis may change erratically by many tens of degrees if the planet has no moon. Because the tilt causes seasons, changes in the tilt will alter the severity of the seasons. Our Moon is large enough that its gravitational attraction on Earth's equatorial bulge helps hold the Earth's tilt relatively fixed, sparing us catastrophically large climate changes.

6.7 MOON LORE

The Moon figures prominently in folklore around the world. Most stories concerning its powers are false. For example, people often claim that the full moon triggers antisocial behavior, hence the term *lunatic.* All studies to look for such effects have found nothing. Automobile accidents, murders, admissions to clinics, and so forth show no increase when the Moon is full.

On the other hand, "once in a blue moon," indicating a rare event, is a phrase with a basis in fact because, on rare occasions, the Moon may look blue. This odd coloration comes from particles in the Earth's atmosphere. Normally, our atmosphere filters the blue colors from light better than the red ones. For example, light from the rising or setting Sun passes through so much atmosphere that little blue light remains by the time it reaches us. Therefore, the Sun looks red when it is low in the sky. However, if the atmosphere contains particles whose size falls within a very narrow range, the reverse may occur. Dust from volcanic eruptions or smoke from forest fires may have just the right size to filter out the red light, allowing mainly the blue colors to pass through. Under these unusual circumstances, we may therefore see a "blue Moon."

A different meaning for "blue moon" has appeared within the last few years. This new meaning applies to months with two full moons. Because the cycle of phases is 29.5 days, unless the Moon is full on the first day of the month, the next full moon will fall in the following month. The odds of the Moon being full on the first of the month are about 1 in 30, and so two full moons in a given month happens about every $2\frac{1}{2}$ years. Why such occasions should be referred to as "blue moons" is controversial.

The harvest moon, the full moon nearest the time of the autumn equinox, is another well-known phrase. As it rises in the east at sunset, the light from the harvest moon helps farmers see to get in the crops. Full moons in other months also have special names, but only the harvest and hunter's moon are widely accepted. Other names occasionally used in American folklore are listed in table 6.3.

TABLE 6.3
Names Used for Full Moons

January	old moon	July	thunder or hay moon
February	hunger moon	August	grain or green corn moon
March	sap or crow moon	September	harvest moon
April	egg or grass moon	October	hunter's moon
May	planting moon	November	frost or beaver moon
June	rose or flower moon	December	long night moon

Summary

The Moon is the Earth's satellite. It is much smaller than the Earth: about one-fourth the Earth's radius and about 1/81 its mass. Its small size has allowed its internal heat to escape, keeping its core cool, thereby preventing plate tectonic motions. The Moon has no atmosphere because it is too cool to create one by volcanic outgassing and too small for its low gravity to retain gases even if an atmosphere had formed.

With neither atmosphere nor tectonic activity, the Moon's surface is unaltered except by impact features: craters, rays, and the maria. Maria are enormous lava flows that have flooded into basins made by large impacting bodies late in the Moon's formation.

The Moon may have formed when a Mars-sized body collided with the Earth and splashed material from the Earth into orbit. That debris, drawn together by its own gravity, would then have reassembled into the Moon.

The Moon's shadow sometimes falls onto the Earth, causing a solar eclipse. When the Earth's shadow falls onto the Moon, we see a lunar eclipse.

The Moon's gravity creates tides, and as the Earth rotates beneath the tidal bulge of the ocean, our planet's rotation is slowed. Similar tidal braking exerted by the Earth on the Moon has slowed the Moon's spin, making it synchronous with its orbital motion around the Earth.

Questions for Review

1. What are the Moon's mass and radius compared with the Earth's?
2. Describe a crater and how it is formed.
3. What are lunar rilles? What are rays?
4. How do the maria differ from the highlands?
5. What formed the maria? Why are they smooth?
6. Why has the Moon no atmosphere?
7. Why is the Moon's surface cratered but the Earth's not?
8. How do astronomers believe the Moon formed? What supports this theory? How does the theory explain why the Earth and Moon have such different densities?
9. How are tides formed on the Earth?
10. Why does the Moon form two tidal bulges on the Earth?
11. Why aren't there eclipses each month?
12. What is an eclipse season?
13. How does the Moon rotate? Why does it spin in this manner?

Thought Questions

1. Why has the Moon's interior cooled more than the Earth's?
2. Bergmann's rule states that individuals of a given species–for example, bears–will be larger in cold climates than in warmer climates. How is an explanation of this rule similar to an explanation of the temperature difference between the Earth's and the Moon's interior?
3. If the day were 12 hours long, what would be the approximate time interval between high and low tide?
4. Highway surfaces develop "potholes" over time. How can you use the number of potholes as an indication of the "age" of the paving? How is this like using craters to estimate the age of the Moon's surface?
5. Why will an astronaut's footprint on the Moon last so long?

Problems

1. A laser pulse takes 2.56 seconds to travel from Earth to the Moon and return. Given that the speed of light is 300,000 kilometers per second, how far away is the Moon?
2. A lunar crater has an angular diameter of 1 minute of arc. What is its diameter in kilometers?
3. A spacecraft orbits the Moon 100 kilometers above its surface and with an orbital period of 114 minutes. What is the Moon's mass?
4. The Moon's orbital period is 27.2122 days. Its synodic period, the period of the phases, is 29.5306 days. Show that 242 orbital periods very nearly equals 223 synodic periods. How long is this in years? What does this suggest about eclipses and why? (This match of cycles is called the *saros* and was used by ancient astronomers to predict eclipses.)
5. Calculate the Moon's density (see end of section 5.1 in the Earth chapter for how to calculate density). The Moon's mass is about 7.3×10^{25} gm, and its radius is about 1.7×10^{8} cm. On the basis of your value for the density, what can you say about the amount of iron in the Moon? (See table 5.1 for iron's density.)

Test Yourself

1. The large number of craters on the lunar highlands compared to those on the maria is evidence that
   (a) the surface of the maria is liquid and craters quickly disappear there.
   (b) the material composing the highlands is very soft and easily cratered.
   (c) the bodies that struck the Moon and made the craters were clumped in such a manner that they missed hitting mare areas.
   (d) the maria are much younger than the highlands.
   (e) the maria are much older than the highlands.
2. Figure 6.19 shows an eclipse of the Sun. The black circle in the middle is
   (a) the Earth's shadow on the Sun.
   (b) the Sun's shadow on the Moon.
   (c) the Moon covering the Sun.
   (d) the Earth's shadow on the Moon.
   (e) a dark cloud in our atmosphere.
3. The photographs above fig. 6.23 were taken at high tide and the next low tide. About how much time elapsed between the pictures?
   (a) 3 hours
   (b) 24 hours
   (c) 12 hours
   (d) 6 hours
   (e) 1 month
4. What evidence indicates that the Moon lacks a large iron core?
   (a) The Moon has a very strong magnetic field.
   (b) The Moon always keeps the same side facing the Earth.
   (c) The Moon has no atmosphere.
   (d) The Moon's average density is about 3.3 grams per cubic centimeter, similar to that of rock.
   (e) The Moon has so many volcanos that all the iron in its core has been erupted onto its surface.
5. Eclipses do not occur each month because
   (a) the Moon's orbit is so elliptical.
   (b) the Moon's orbit is tilted with respect to the Earth's orbit around the Sun.
   (c) the Moon takes 6 months to complete its orbit around the Earth.
   (d) the Earth's rotation axis is tilted.
   (e) the statement is false. Eclipses do occur each month, but they are generally visible only in very remote parts of the Earth.

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Web site

Please visit the *Explorations* web site at **http://www.mhhe.com/arny** for additional on-line resources on these topics.

Key Terms

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